ENVIRONMENTAL RESEARCH
LETTERS

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To cite this article before publication: Haiwei Li *et al* 2023 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ad0a56

Relating Three-Decade Surge in Space Cooling Demand to Urban Warming

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Keywords: urban space cooling demand, three-decade urban warming, urban heat island, extreme heat events, behavioral adaptation, five populated cities.

Abstract

Rising demand for space cooling has been placing enormous strain on various technological, environmental, and societal dimensions, resulting in issues related to energy consumption, environmental sustainability, health and well-being, affordability, and equity. Holistic approaches that combine energy efficiency optimization, policy-making, and societal adaptation must be rapidly promoted as viable and timely solutions. We interpret the 30-year climatic-induced upward trend and spikes in urban space cooling demand from the perspective of climate change, urbanization, and background climates, through the lens of five major populated cities: Hong Kong, Sydney, Montreal, Zurich, and London. An unequivocal, worrying upward trend in cooling demand is observed in meteorological data, using cooling degree hours (CDH) as a city-scale climatic-induced metric. The surge in cooling energy demand can be largely attributed to climate warming and urban heat islands, with the most abrupt spikes associated with intensified extreme heat events. Further, our quantification of the impact of the base temperature, in relation to the historical CDH, reveals that a 20% energy saving could be achieved instantly within a rather broad range of air temperature and relative humidity by increasing the setpoint temperature by one degree. With the rise in background temperatures due to climate change, the potential for energy saving diminishes for the same level of increase in setpoint temperature. For instance, an increase from 26 °C to 27 °C results in about 10% energy savings, while an increase from 22 °C to 23 °C could yield over

20% in energy savings. To reduce cooling energy demand rapidly in a warming climate, we highlight the necessity of promoting hard and soft behavioral adaptation along with regulatory intervention for the operation of space cooling systems.

1. Introduction

The building sector is responsible for 30% of global energy consumption and 27% of total energy emissions (IEA 2022). Currently, 56% of the world's population lives in urban areas, and this percentage is expected to increase to 68% by 2050 (DESA 2018), escalating the energy burden in cities. The energy demand for space heating or cooling is determined by building design and operation, building physical properties and occupancy activities, socio-economic factors such as the air conditioning technology and level of urbanisation, and most importantly, climatic conditions such as the air temperature (Biardeau *et al* 2020, Ürge-Vorsatz *et al* 2015, Zhao *et al* 2023, Jia *et al* 2017). As global warming intensifies, it becomes increasingly crucial to prioritize the analysis of climate-induced, especially air temperature-induced cooling demand trends across diverse climates, encompassing both urban and rural areas. The earth's average surface temperature has risen by approximately 1.2 °C since the late 19th century (Masson-Delmotte *et al* 2018). Meanwhile, the frequency, duration, and severity of extreme temperature events, such as heatwaves and record-breaking high temperatures, are aggravated (Coumou and Rahmstorf 2012). Due to the urban heat island (UHI) effect, these events occur more often in urban areas than in the surrounding suburban or rural areas (Zhao *et al* 2014). The UHI effect exacerbates the overheating in cities, leading to high heat-related illness and higher mortality rates, increased building cooling energy demand, air pollution associated with the high temperatures and reduced ventilation, and a potential energy crisis among a large portion of the global population (Li *et al* 2019). From June 2022 to August 2022, heatwaves in Europe were reported as the most deadly meteorological events and they have caused more than 20,000 heat-related deaths. The global air-conditioning demand is expected to increase rapidly, and it is expected that the electricity demand for cooling in 2100 will be 40 times greater than it was in 2000 (Isaac and van Vuuren 2009). Understanding the long-term trend of climatic-induced cooling energy demands in both urban and rural areas is crucial.

For a 30-year period, we analyzed the climatic-induced, especially temperature-induced cooling demand and the principal climatic drivers, such as warming background climate by climate warming, urban heat island (UHI), heatwaves, and some potential mitigation measures for five cities residing in different climates: Hong Kong, Sydney, Montreal, Zurich, and London. The cooling demand for urban and rural (or suburban) areas is quantified by yearly cooling degree hours

(CDH) calculated from climatological standard 30-year (from 1990 to 2021) observation data. Previous research on climate-induced cooling energy analysis using the CDH or cooling degree days (CDD) model traditionally focused on the indoor cooling system at building scale (Bolattürk 2008, Oktay *et al* 2011), and at city and country scale for specific forecasted years (Salata *et al* 2022, Odou *et al* 2023). In our study, both the analysis of space cooling demand and the three-decade hourly dataset on air temperature and CDH serve as valuable resources for the community. Our research is centered on the relationship between cooling energy demand and the ongoing warming urban climate. Concurrently, our work provides energy-saving recommendations encompassing behavioral adaptation and regulatory interventions. These suggestions can potentially enhance public awareness about improving adaptive thermal comfort standards and adopting sustainable energy practices in a changing climate.

2. Methods

2.1 Study sites

In order to investigate the cooling demand variation related to air temperature across regions with diverse climate types, urban morphology patterns, and levels of urbanization, we conducted an analysis of climatic data in urban and suburban/rural areas of five cities: Hong Kong, Sydney, Zurich, Montreal, and London. The selection of the five cities was based on their high levels of urbanization and population densification, the presence of severe heat stress and energy-related challenges, and the availability of high-quality meteorological data. Notably, the European cities among these have experienced record-breaking heatwaves and energy crises in recent years (Rousi et al., 2022; Ward et al., 2016). Although our selected cities encompass regions in Europe, Asia, Australia, and North America, predominantly characterized by temperate and continental climates, we recognize the limitation in representing areas such as Africa and South America, as well as diverse climatic zones.

The selection of urban and suburban/rural sites was based on the local climate zone (LCZ) classification, a widely recognized standard in UHI research for classifying urban morphologies and natural landscapes. The LCZ classification system consists of ten built-up classes and seven land cover types (Lau *et al* 2019), providing a comprehensive parameterization of characteristics such as building height and coverage, pervious/impervious cover, aspect ratio, and surface materials (Núñez Peiró *et al* 2019). The suburban/rural sites were selected by evaluating LCZ built types and land cover (Demuzere *et al* 2022), while being 5-40 km away from the corresponding urban sites. In the sites we selected, the largest distance between urban and rural areas is 34.18 km in Montreal, between Trudeau and Mirabel airports.

Hong Kong falls within the monsoon-influenced humid subtropical climate zone (Köppen climate classification: Cwa), while Sydney is classified as humid subtropical (Cfa). Both cities experience hot and humid summers, along with cool to mild winters, with monthly mean temperatures exceeding 18 °C and less pronounced dry seasons. The urban site in Hong Kong is situated at the Observatory Headquarters (latitude, longitude: 22.30, 114.17) with LCZ-1 compact highrise built type, and the suburban site is located in Ta Kwu Ling (22.53, 114.16) with LCZ-6 open lowrise built type. In Sydney, the urban site is located in Bankstown (latitude, longitude: -33.92, 150.98) with LCZ-2 compact midrise built type, while the suburban site is situated in Observatory Hill (-33.86, 151.20) at the boundary of the city with a mixture of G-water land cover and LCZ-5 open midrise.

Montreal belongs to the warm-summer humid continental climate zone (Dfb), characterized by four distinct seasons, significant temperature variations throughout the year, and moderately distributed precipitation. The urban site in Montreal is found in Trudeau airport (latitude, longitude: 45.47, -73.74) with LCZ-5 open midrise built type, and the suburban site is located in Mirabel airport (45.68, -74.04) with A-dense tree land cover.

Zurich exhibits a climate that lies between the warm-summer humid continental (Dfb) and temperate oceanic (Cfb) zones. Similarly, London falls within the temperate oceanic climate zone (Cfb). These cities experience cool summers and mild winters, with relatively narrow monthly mean temperature ranges and low seasonal variations. The urban site in Zurich is situated in Kaserne (latitude, longitude: 47.38, 8.53) with LCZ-2 compact midrise built type, while the rural site is located in Kloten (47.29, 8.32) with D-low plants land cover. In London, the urban site is located in St James' Park (latitude, longitude: 51.50, -0.23) with LCZ-4 open highrise built type, and the rural site is situated in Kenley (51.30, -0.09) with B-scattered tree land cover.

2.2 Meteorological data and cooling degree hour (CDH) calculation

The analysis utilizes three decades' hourly air temperature data at the two-meter height at the selected weather stations. This parameter is the ambient temperature at two meters above surfaces of land, sea or water, which is valuable thermal information on outdoor pedestrian conditions (Stathopoulos 2006). The time period of data is subject to the data availability of the local weather stations, Hong Kong (urban and suburban: 1990 to 2021), Sydney (urban: 1993 to 2021, suburban:

1991 to 2021), Montreal (urban and rural: 1990 to 2021), Zurich (urban: 1991 to 2020, rural: 1990 to 2020), London (urban and rural: 1990 to 2021).

In order to quantify the air temperature-related space cooling load pattern, this work employs cooling degree hour (CDH) calculation, a non-invasive measurement to analyze the accumulated cooling needs over a specific time period based on the climatic change of the outdoor environment. It provides energy consumption patterns in relation to weather conditions rather than exact values of cooling loads. CDH is a common tool for understanding the energy trends and extremes caused by climatic conditions and variations (Salata *et al* 2022, McGarity and Gorski 1984). And it is useful in comparative analysis over a long period of time among multiple areas and making potential cooling efficiency improvements based on comparative analysis.

CDH has been traditionally employed in recognized guidelines and protocols (ASHRAE 2005) and peer-reviewed articles for assessing indoor cooling system at the building scale (Bolattürk 2008, Oktay *et al* 2011), and CDD has been recently used in energy demand assessment for current and future projections at both city and country scales (Odou *et al* 2023, Spinoni *et al* 2018, Salata *et al* 2022). The mathematical expression is defined by ASHRAE, which is presented in Equation 1 (ASHRAE 2005, Kong *et al* 2023).

$$\mathrm{CDH} = \sum_{k=0}^{n} \begin{cases} t_{oa,k} - t_b\,, & t_{oa,k} > t_b \\ 0, & t_{oa,k} \le t_b \end{cases} \tag{1}$$

where n is the total number of hours, t_b represents the base temperature and $t_{oa,k}$ is the outdoor ambient temperature at the measurement hour k.

For our study, this metric utilizes outdoor air temperature data, $t_{oa,k}$, measured at 2m height at weather stations. The base temperature, t_b, is typically chosen as the setpoint temperature for air conditioning systems, indicating the threshold above which the air conditioning system operates. In the context of air conditioning at the building scale, the choice of the base temperature is subject to various influences, including local context, cultural factors, individual preferences, and may even evolve over time (Bhatnagar *et al* 2018, Murakami *et al* 2009). However, for the purpose of our research, which centers on long-term analysis of climate-induced trends using the CDH model, it is practical to opt for a consistent base temperature within the acceptable range of thermal comfort.

Compared to standard building energy modeling, CDH calculations come with limitations in accounting for specific building characteristics like occupancy, building materials, the intricacies of cooling and heating systems and the penetration of the air conditioning system. With consideration of the increasing penetration of the air condition system, the actual CDH for space cooling would differ from the amount we determined. Furthermore, they overlook high humidity-induced additional energy consumption. To address this, Feng *et al* (2021) proposed modeling humidity-induced building cooling energy demand using low humidity hours (LHH) and high humidity hours (HHH) as complements to traditional CDH models. Other humidity-correlated calculation are the humidity-corrected cooling degree hour (CDHhum) (Scoccimarro *et al* 2023) and enthalpy-based CDD (Krese *et al* 2011, Shin and Do 2016). They are similar to CDH, but calculated combining the effects of air temperature and relative humidity, instead of relying on air temperature (Scoccimarro *et al* 2023).

However, it is worth noting that while mechanical cooling systems with embedded humidity control are influenced by external humidity levels, research has shown that CDH and dry bulb temperature remain the most statically the most significant parameters impacting cooling energy consumption. Notably, they contribute to an R^2 of over 91% in predicting cooling energy demand (Feng *et al* 2021). Enhancing the model by incorporating relative humidity, LHH and HHH have not been found to offer statistically significant improvements in determining space cooling energy. Recent work by Odou et al (2023) has shown that cooling degree days (CDD), a similar cooling demand evaluation model without considering changes in humidity, serves as an effective metric to analyze long-term trends and provide comparative analysis of cooling energy due to air temperature changes on both regional and national scales. Consequently, in our study, CDH is a robust tool, using hourly time-resolution air temperature data, suitable for investigating accumulated cooling demand trends and conducting comparative analyses over a long period of three decades across major populated cities and climates.

3. Results and discussion

3.1 Relating cooling demand to background climates and urbanization

Figure 1 (a) shows the results of CDH calculations for the five cities mentioned above from 1990 to 2021, demonstrating yearly cooling energy demand in all five cities during the last three decades. The main climate driver of energy demand is the ambient background temperature during the cooling season (van Ruijven *et al* 2019). The increasing trend has a robust association with the temperature, including increasing time-averaged temperature, increasing peak temperatures, and heatwave events during the cooling season. The background climatology determines the distinct difference in the magnitudes of the cooling demand in five cities.

The cooling season refers to the period that requires cooling to maintain the inside building temperature below the setpoint temperature. Both Hong Kong and Sydney have a cooling season from Spring to Autumn, while the cooling season for Montreal, Zurich, and London is mostly Summer, from June to August. Hong Kong shows a value of CDH in the range of 25 to 33 k°C·h and Sydney shows a CDH in the range of 2 to 10 k°C·h. Montreal and Zurich show CDH ranging from 1 to 7 k°C·h. Moreover, London has CDH values up to 3 k°C·h. The results of CDH show that the warmer subtropical cities, i.e., Hong Kong and Sydney, have distinctly higher cooling demand and longer cooling seasons than Montreal, Zurich, and London.

Due to the nature of CDH calculation and data availability, our analysis (Figure 1a) shows the cooling demand patterns associated with air temperature. In the actual setting, population density growth (as illustrated in Figure 1b) contributes to the increase in anthropogenic heat. This heat is one of the main factors leading to urban overheating and changes in space cooling demand. For example, Spinoni et al. (2018) have incorporated population weighting in CDH to analyze the socio-economic sensitivity. Since our focus is the climate-induced cooling load quantification and also the detailed socio-economic change during three decades is not available in all five cities, we did not incorporate socio-economic aspects in our CDH calculation. Reflecting the contribution of socio-economic induced aspects and complement the CDH calculation, the trend of population density (Figure 1a) in all five cities also indicates the urbanization and potential social and economic development of these cities during the last three decades. The relationship between population densification, urbanization, socio-economic development, and the prevalence of air conditioning systems is a subject of critical importance, as it bears implications for both energy demand and environmental sustainability (Hassan and Lee 2015). The migration of population, typically concomitant with socio-economic development, manifests in increased disposable income, improved living standards, and access to modern amenities. Advancements in technology have led to a reduction in the cost of air conditioning systems, rendering them more accessible to a broader spectrum of urban populations (Sailor and Pavlova 2003, Waite *et al* 2017). As a result, the actual cooling consumption of these cities is influenced by multifaceted factors, which could be potentially higher than our reported climatic-induced values (Manoli *et al* 2019).

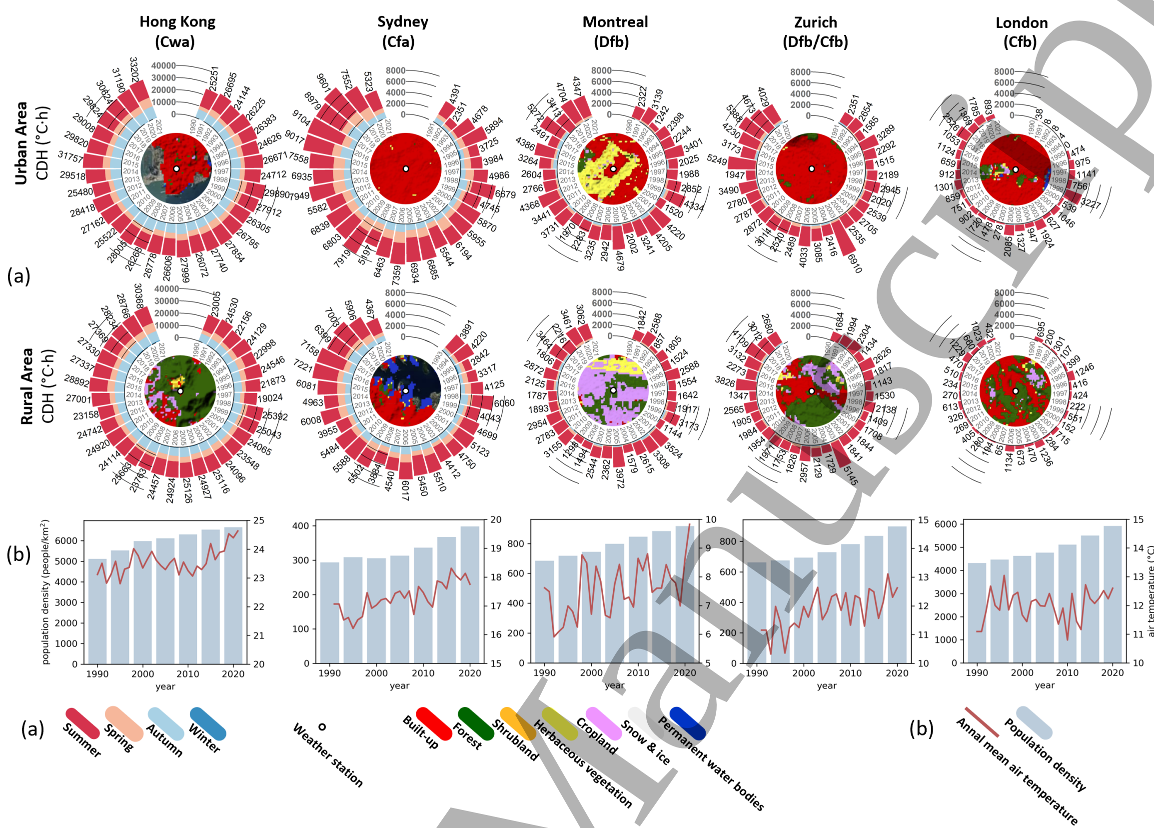

Figure 1. (a) Yearly cooling degree hours (CDH) of urban and rural areas (or suburban) in Hong Kong, Sydney, Montreal, Zurich, and London from 1990 to 2021. The base temperature for CDH calculation is 22 °C. The graphs in the center of each circular plot display the land types within 3 km of the weather stations. Remark the maximum scale for Hong Kong, 40,000 is different from the other cities with a maximum scale of 8,000. (b) Population growth (bars) and annual mean urban air temperature rise (lines) from 1990 to 2021. Note that the sub-figures have different scales of the y-axis for different cities.

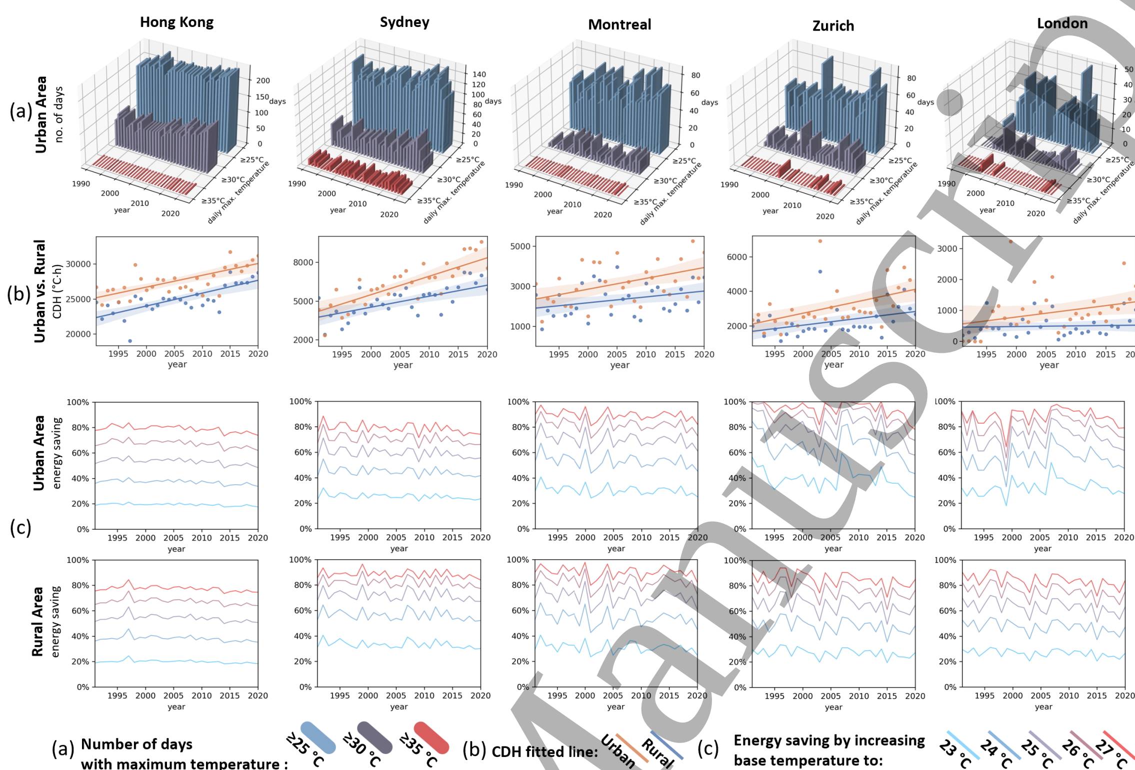

Figure 2. (a) The number of days with maximum air temperature ≥25, 30, 35 °C in the urban areas of Hong Kong, Sydney, Montreal, Zurich, and London, based on the calculation of climate norms stated in WMO 2017 Guidelines (Arguez and Vose 2011). (b) Yearly urban and rural CDH with fitted trend-lines (orange: urban, blue: rural/suburban). The CDH data are calculated based on base temperature, i.e., 22 °C. (c) Energy saving or CDH reduction by increasing the base temperature from 22 °C to 23-27 °C. The increase in the base temperature reflects the potential impact of behavioral adaptation and regulatory intervention for spacing cooling.

3.2 Three-decade space cooling demand in warming climates

In Figure 2 (b), the mean trend-lines of CDH show an approximate increase rate of 160 °C·h per year (170 °C·h per year) over the last 30 years of urban (suburban) Hong Kong, 120 °C·h per year (70 °C·h per year) for urban (suburban) Sydney, 50 °C·h per year (20 °C·h per year) for urban (rural) Montreal, 30 °C·h per year (25 °C·h per year) for urban (rural) Zurich and 25 °C·h per year (5 °C·h per year) for urban (rural) London.

With the ongoing urbanization, the escalation of energy demand and consumption, particularly during the summer months in cities and countries, can be attributed to two significant factors: global warming and the UHI effect (Morakinyo *et al* 2019, Santamouris *et al* 2001, Tian *et al* 2021). In one previous study, Santamouris (2014) summarized the impacts of UHI in the existing case studies, where they estimated that UHI intensity contributes to an average of 13% higher cooling load for urban buildings compared to their rural counterparts during the period from 1970 to 2010. From Figure 2b, our results showed the persistent increase trend in cooling demand for both urban and rural areas, as well as the disparities in cooling demand between urban and rural areas, which is associated with UHI effects. Compared to the baseline figures in 1990, the CDH increased by 20% (23%) for urban (suburban) Hong Kong, 100% (83%) for urban (suburban) Sydney, 60% (50%) for urban (rural) Montreal, 100% (65%) for urban (rural) Zurich and 160% (30%) for urban (rural) London.

The trend lines in Figure 2b indicate that for all cities, the relative increase in CDH is higher in urban areas, especially within LCZ highrise and midrise built zones, when compared to rural regions classified as LCZ-A, B, and G (Trees and Water). The surge in space cooling demand, alongside the spikes in CDH in urban areas and the distinction in LCZ types between urban and rural areas, underscores the contribution of urbanisation, population densification and anthropogenic heat release. The LCZ built types and land covers in urban-rural difference influences the spatial heterogeneity of UHI effect which leads to variations of levels of cooling demand magnitudes (Chakraborty *et al* 2022). It highlights the reduction in evapotranspiration and convection efficiency as a result of reduction in greenery coverage in LCZ highrise and midrise built zones (Krayenhoff *et al* 2021, Zhao *et al* 2021, Paschalis *et al* 2021). More advanced earth observations of extreme heat events in urban areas could aid in mitigating overheating (Zaitchik and Tuholske 2021) and the increasing spikes in CDH (Larsen *et al* 2020).

As presented in Figure 1 (a), urban areas have more impervious heat-storing built-ups and less vegetation or water bodies than rural areas, meaning low water availability and evapotranspiration in urban environments, leading to high urban-rural temperature differences and higher cooling demand in urban areas (Zhao *et al* 2023, Yang *et al* 2022). The convection efficiency, which is associated with changes in the aerodynamic resistance, represents the heat transfer from the surfaces of buildings to the atmosphere (Zhao *et al* 2014). The high aerodynamic resistance of urban areas results in low efficient convection, which reduces the convection efficiency and increases the UHI intensity and cooling demand. Re-introducing green spaces and water surfaces into the urban area could increase both evapotranspiration and convection efficiency, and effectively reduce the energy demand for cooling.

3.3 Cooling demand spikes in extreme heat events and heatwaves

Extreme heat events, often referred to as high-temperature events, are characterized by the number of days during which the maximum temperature surpasses 25 °C, 30 °C, and 35 °C. These thresholds shown in Figure 2 (a) are consistent with the criteria set forth by the WMO Guidelines (Arguez and Vose 2011). The demand for space cooling can more than double in response to the exceptionally high frequency and prolonged duration of summer heat events (Falasca *et al* 2019, Frank 2005, Zinzi *et al* 2020). During years marked by severe extreme heat events, as indicated by the spikes in air temperatures depicted in Figure 2a, urban areas experience substantial surges. This is further emphasized by the CDH outliers surpassing the trend seen in Figure 2b. Such surges are most pronounced in London, where the CDH can surge by as much as 305%. Meanwhile, there are increases of 130% in Zurich, 49% in Montreal, 34% in Sydney, and 15% in Hong Kong in comparison to the average of the previous year.

In the heatwave period in 2020, CDH takes up above 71% (urban Hong Kong), 60% (urban Sydney), 46% (urban Montreal), 44% (urban Zurich), and 47% (urban London) of the total CDH for the whole year. The cooling load is more than doubled in the years with exceptionally high frequency and high duration of summer heat events. The increasing trends of CDH are relatively smooth in Hong Kong, Sydney, and Montreal, while the spikes in CDH is more frequently seen in western Europe, e.g., London and Zurich. Rousi et al. (2022) have identified Europe as a 'heatwave spot' since its increase in the occurrences of extreme heat has been three-to-four times more frequent than for other northern mid-latitude regions over the past decades, which is mainly due to the increasing trend in the persistence of double jet occurrences. Zurich and London suffered from the record-breaking heatwave that prevailed in Europe in the year 2003. That severe heatwave is still considered to be the warmest period of the last 500 years, which not only caused energy consumption to increase but also burdened health and emergency services in Europe, leading to over tens of thousands of excess deaths. Recently, an exceptional heatwave event affected the U.K. in July 2022, reaching 40 °C for the first time and causing over 2,800 excess deaths in the elder population. In Switzerland, MeteoSwiss activated orange and yellow alerts for heatwaves in 2022 and recorded a temperature up to 38.3 °C in August 2022. Urgent and effective climate-sensitive urban planning with sustainable and resilient mitigation measures is critical to tackling future energy demand spikes.

3.4 Energy saving potential by behavioral adaptation and regulatory intervention

As the base temperature is increased to 23-27 °C, energy saving or CDH reduction with respect to that at the base temperature of 22 °C is significant (Figure 2c). The base temperature is a fundamental consideration in CDH analysis, above which cooling is required. The base temperature is the setpoint temperature of air conditioning systems chosen based on the relationship between local climate, occupancy activities, building properties and functions, air conditioning systems and cultural factors. Prior research used a common base temperature of around 22 °C for CDH calculations (Bolattürk 2008).

Behavioral adaptation, in the context of raising the base temperature for cooling systems, refers to proactive changes humans undertake in their daily habits to adapt to warmer indoor temperature, while maintaining acceptable comfort and energy efficiency (Arsad *et al* 2023). Such changes involve conscious actions and choices made by individuals or occupants to mitigate the effects of warmer indoor environments, including choosing lighter clothes, implementing passive or natural ventilation, utilizing greenery as shading, and adjusting acceptable thermal comfort levels (Ban *et al* 2019, Gangiah 2021). Upgrading the building cooling system using an adaptive comfort approach and higher thermostat setpoints, such as the Cool Biz approach in Japan (Murakami *et al* 2009), increases the base temperature for indoor space cooling. The cooling demand can be approximately reduced by 20% as the base temperature is merely increased by one degree, i.e., from 22 °C to 23 °C, implying that behavioral adaptation may make an immediate difference in achieving desired energy saving without compromising thermal comfort considerably. Although setpoint air temperature is usually considered the most crucial parameter in determining thermal comfort in an indoor environment, behavioral adaptation for other setpoint parameters, such as the indoor humidity level, is also necessary for maintaining the acceptable adaptive comfort level in an indoor environment (ASHRAE 2005).

We have chosen the base temperature or setpoint temperature based on the thermal comfort assessment, which is a comprehensive assessment combining air temperature, humidity level, airspeed, and metabolic rate. High humidity levels can hinder sweat evaporation from the skin, eventually causing extra discomfort or even dangerous heat stress for urban residents under heat waves and extreme weather (Zhang *et al* 2023, Chakraborty *et al* 2022). Standard Effective Temperature (SET) is a thermal comfort index that combines various environmental parameters to estimate the perceived temperature and physiological responses of individuals in a given environment (Tartarini *et al* 2020, Zhang and Lin 2020, Ji *et al* 2022, Arguez and Vose 2011). As an illustrative example, we present the impact of changing setpoint temperature and relative humidity on indoor thermal comfort in Appendix A. The significance of adjusting the relative humidity setpoint, in order to preserve physiological thermal neutrality when elevating the base temperature – thereby achieving energy saving, cannot be overstated. When adjusting the indoor setpoint relative humidity while maintaining a fixed setpoint air temperature, variations in SET values of up to 1.7 °C can occur. When raising the setpoint air temperature to 26°C, it is essential to keep the setpoint relative humidity below 40% to maintain physiological thermal neutrality. Therefore, increasing base temperature for energy-saving improvements may require consideration of other parameters, including humidity, airspeed and and metabolic rate to ensure comfortable thermal environment.

As depicted in Figures 2b and 2c, the analysis of raising base temperature reveals notable variations in energy saving potentials across different years, cities, climates, and urban or rural areas. The potential for energy savings resulting from a 1 °C increase in the base temperature has shown a slight reduction over the past three decades, with the continuous growth in CDH. The urban energy saving potentials are within 5%, slightly higher than the rural energy saving potential. Notably, the relationship between raising the base temperature and the percentage of energy saving potential is not linearly related; for example, elevating the base temperature from 22°C to 23°C generally yields the most substantial energy saving potential. Conversely, raising the base temperature from 26°C to 27°C has a relatively limited impact on increasing energy saving potential. Specifically, the former contributes to over 20% of the overall energy saving potential, while the latter accounts for less than 10%, as presented in Figure 2c.

Furthermore, it is essential to note that the strategy of raising the base temperature proves to be less effective, with energy saving 5% lower than in regular years, in mitigating cooling demand spikes induced by extreme heat events in specific years. This highlights the critical need for implementing additional heat-resilient design strategies and passive survivability (Baniassadi *et al* 2019), when the option of adaptive approaches reaches its limitations. Potential practical measures could be pre-cooling to improve residential buildings' thermal resilience during heatwave (Zeng *et al* 2022). Therefore, it should be thoroughly analyzed when introduced to urban areas where heatwaves are increasingly common. Such multifaceted discussions are indispensable in addressing the challenges posed by climate change and its impacts on cooling demand in various climate and urban/rural contexts.

Renovating existing building systems in terms of improving energy performance is crucial worldwide, as pointed out by the Commercial Building Disclosure (CBD) program in Australia and in the Annex projects launched by the International Energy Agency (IEA). Effective regulatory intervention on building energy retrofitting and operation codes should be a preferred instrument for policymakers aiming to rapidly reduce energy consumption for space cooling.

4. Conclusion

Our research, analyzing meteorological data in five major populated cities, Hong Kong, Sydney, Montreal, Zurich, and London, reveals a significant climatic-induced upward trend in cooling demand over the past three decades.

The background climates, impervious built-up surfaces, population density, and some socio-economic factors largely influence the cooling demand in cities. Additionally, extreme heat events and heatwave events can result in more than doubled cooling spikes in urban areas, which are evident in heatwaves occurred in European cities (London and Zurich). The significance of the selection of the base temperature is noted. The energy-saving potential achieved through an increase in the base temperature varies depending on several contextual factors, including the regional climate, whether the location is urban or rural, and the specific time. Implementing an effective energy-saving strategy involving an adaptive thermal comfort assessment requires a comprehensive assessment beyond merely altering the setpoint air temperature. It should consider various setpoint parameters aimed at sustaining a comfortable perceived thermal environment for occupants, taking into account factors such as humidity and other comfort-related factors. The quantification of the impact of base temperature on cooling degree hours (CDH) indicates that a one-degree increase in setpoint temperature, with behavioral adaptation or regulatory intervention on the operation of space cooling systems, could result in 20% energy savings. While there are still some critical drivers, such as energy policy, occupant behavior, socio-cultural practices, and indoor cooling technology, that require deeper understanding and solution, our findings offer insights into the climate factors and the development of rapid and feasible energy-saving solutions in a warming climate.

Acknowledgment

The authors wish to acknowledge the meteorological data provided by the Australian Bureau of Meteorology and Hong Kong Observatory.

Data availability

The ambient temperatures and CDH dataset is available via https://github.com/florahww/Urban-Cooling-Data.git. The dataset will also be on the website of the Chair of Building Physics, ETH Zurich after publishment.

References

Arguez A and Vose R S 2011 The definition of the standard WMO climate normal: The key to deriving alternative climate normals *Bull Am Meteorol Soc* **92**

Arsad F S, Hod R, Ahmad N, Baharom M and Ja'afar M H 2023 Assessment of indoor thermal comfort temperature and related behavioural adaptations: a systematic review *Environmental Science and Pollution Research* **30**

ASHRAE 2005 *ASHRAE Handbook Fundamentals 2005*

Ban J, Shi W, Cui L, Liu X, Jiang C, Han L, Wang R and Li T 2019 Health-risk perception and its mediating effect on protective behavioral adaptation to heat waves *Environ Res* **172**

Baniassadi A, Sailor D J, Scott Krayenhoff E, Broadbent A M and Georgescu M 2019 Passive survivability of buildings under changing urban climates across eight US cities *Environmental Research Letters* **14**

Bhatnagar M, Mathur J and Garg V 2018 Determining base temperature for heating and cooling degree-days for India *Journal of Building Engineering* **18**

Biardeau L T, Davis L W, Gertler P and Wolfram C 2020 Heat exposure and global air conditioning *Nat Sustain* **3**

Bolattürk A 2008 Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey *Build Environ* **43**

Chakraborty T, Venter Z S, Qian Y and Lee X 2022 Lower Urban Humidity Moderates Outdoor Heat Stress *AGU Advances* **3**

Coumou D and Rahmstorf S 2012 A decade of weather extremes *Nat Clim Chang* **2**

Demuzere M, Kittner J, Martilli A, Mills G, Moede C, Stewart I D, Van Vliet J and Bechtel B 2022 A global map of local climate zones to support earth system modelling and urban-scale environmental science *Earth Syst Sci Data* **14**

DESA U 2018 68% of the world population projected to live in urban areas by 2050, says UN *United Nations Department of Economic and Social Affairs*

Falasca S, Ciancio V, Salata F, Golasi I, Rosso F and Curci G 2019 High albedo materials to counteract heat waves in cities: An assessment of meteorology, buildings energy needs and pedestrian thermal comfort *Build Environ* **163**

Feng Y, Duan Q, Chen X, Yakkali S S and Wang J 2021 Space cooling energy usage prediction based on utility data for residential buildings using machine learning methods *Appl Energy* **291**

Frank T 2005 Climate change impacts on building heating and cooling energy demand in Switzerland *Energy Build* **37**

Gangiah S 2021 Behavioural adaptation: A review of adaptation to workplace heat exposure of kitchen workers with reference to gender differences in durban *HTS Teologiese Studies / Theological Studies* **77**

Hassan A M and Lee H 2015 Toward the sustainable development of urban areas: An overview of global trends in trials and policies *Land use policy* **48**

IEA 2022 *Tracking buildings 2022* (Paris: IEA Paris, France) Online: https://www.iea.org/reports/buildings

Isaac M and van Vuuren D P 2009 Modeling global residential sector energy demand for heating and air conditioning in the context of climate change *Energy Policy* **37**

Ji W, Zhu Y, Du H, Cao B, Lian Z, Geng Y, Liu S, Xiong J and Yang C 2022 Interpretation of standard effective temperature (SET) and explorations on its modification and development *Build Environ* **210**

Jia M, Srinivasan R S and Raheem A A 2017 From occupancy to occupant behavior: An analytical survey of data acquisition technologies, modeling methodologies and simulation coupling mechanisms for building energy efficiency *Renewable and Sustainable Energy Reviews* **68**

Kong J, Zhao Y, Strebel D, Gao K, Carmeliet J and Lei C 2023 Understanding the impact of heatwave on urban heat in greater Sydney: Temporal surface energy budget change with land types *Science of The Total Environment* **903** 166374 Online: https://www.sciencedirect.com/science/article/pii/S0048969723049999

Krayenhoff E S, Broadbent A M, Zhao L, Georgescu M, Middel A, Voogt J A, Martilli A, Sailor D J and Erell E 2021 Cooling hot cities: a systematic and critical review of the numerical modelling literature *Environmental Research Letters* **16**

454 Krese G, Prek M and Butala V 2011 Incorporation of latent loads into the cooling degree days concept *Energy Build* **43**

456 Larsen M A D, Petrović S, Radoszynski A M, McKenna R and Balyk O 2020 Climate change impacts on trends and extremes in future heating and cooling demands over Europe *Energy Build* **226**

459 Lau K K L, Chung S C and Ren C 2019 Outdoor thermal comfort in different urban settings of sub-tropical high-density cities: An approach of adopting local climate zone (LCZ) classification *Build Environ* **154**

462 Li X, Zhou Y, Yu S, Jia G, Li H and Li W 2019 Urban heat island impacts on building energy consumption: A review of approaches and findings *Energy* **174**

464 Manoli G, Fatichi S, Schläpfer M, Yu K, Crowther T W, Meili N, Burlando P, Katul G G and Bou-Zeid E 2019 Magnitude of urban heat islands largely explained by climate and population *Nature* **573**

467 Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla P R, Pirani A, Moufouma-Okia W, Péan C, Pidcock France R, Connors S, Matthews J B R, Chen Y, Zhou X, Gomis M I, Lonnoy E, Maycock T, Tignor M and Waterfield T 2018 *Summary for Policymakers. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5 °C above pre-industrial levels.*

472 McGarity A E and Gorski A I 1984 PASSIVE GENERATION AND STORAGE OF WINTER ICE FOR SUMMER COOLING APPLICATIONS.

474 Morakinyo T E, Ren C, Shi Y, Lau K K L, Tong H W, Choy C W and Ng E 2019 Estimates of the impact of extreme heat events on cooling energy demand in Hong Kong *Renew Energy* **142**

476 Murakami S, Levine M D, Yoshino H, Inoue T, Ikaga T, Shimoda Y, Miura S, Sera T, Nishio M, Sakamoto Y and Fujisaki W 2009 Overview of energy consumption and GHG mitigation technologies in the building sector of Japan *Energy Effic* **2**

479 Núñez Peiró M, Sánchez-Guevara Sánchez C and Neila González F J 2019 Source area definition for local climate zones studies. A systematic review *Build Environ*

481 Odou O D T, Ursula H H, Adamou R, Godjo T and Moussa M S 2023 Potential changes in cooling degree day under different global warming levels and shared socioeconomic pathways in West Africa *Environmental Research Letters* **18**

Oktay Z, Coskun C and Dincer I 2011 A new approach for predicting cooling degree-hours and energy requirements in buildings *Energy* **36**

Paschalis A, Chakraborty T, Fatichi S, Meili N and Manoli G 2021 Urban Forests as Main Regulator of the Evaporative Cooling Effect in Cities *AGU Advances* **2**

Rousi E, Kornhuber K, Beobide-Arsuaga G, Luo F and Coumou D 2022 Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia *Nat Commun* **13** 3851 Online: https://doi.org/10.1038/s41467-022-31432-y

van Ruijven B J, de Cian E and Sue Wing I 2019 Amplification of future energy demand growth due to climate change *Nat Commun* **10**

Sailor D J and Pavlova A A 2003 Air conditioning market saturation and long-term response of residential cooling energy demand to climate change *Energy* **28**

Salata F, Falasca S, Ciancio V, Curci G, Grignaffini S and de Wilde P 2022 Estimating building cooling energy demand through the Cooling Degree Hours in a changing climate: A modeling study *Sustain Cities Soc* **76**

Santamouris M 2014 On the energy impact of urban heat island and global warming on buildings *Energy Build* **82**

Santamouris M, Papanikolaou N, Livada I, Koronakis I, Georgakis C, Argiriou A and Assimakopoulos D N 2001 On the impact of urban climate on the energy consumption of buildings *Solar Energy* **70** 201–16 Online: https://www.sciencedirect.com/science/article/pii/S0038092X00000955

Scoccimarro E, Cattaneo O, Gualdi S, Mattion F, Bizeul A, Risquez A M and Quadrelli R 2023 Country-level energy demand for cooling has increased over the past two decades *Commun Earth Environ* **4**

Shin M and Do S L 2016 Prediction of cooling energy use in buildings using an enthalpy-based cooling degree days method in a hot and humid climate *Energy Build* **110**

Spinoni J, Vogt J V., Barbosa P, Dosio A, McCormick N, Bigano A and Füssel H M 2018 Changes of heating and cooling degree-days in Europe from 1981 to 2100 *International Journal of Climatology* **38**

Stathopoulos T 2006 Pedestrian level winds and outdoor human comfort *Journal of Wind Engineering and Industrial Aerodynamics*

Tartarini F, Schiavon S, Cheung T and Hoyt T 2020 CBE Thermal Comfort Tool: Online tool for thermal comfort calculations and visualizations *SoftwareX* **12**

Tian L, Li Y, Lu J and Wang J 2021 Review on urban heat island in china: Methods, its impact on buildings energy demand and mitigation strategies *Sustainability (Switzerland)* **13**

Ürge-Vorsatz D, Cabeza L F, Serrano S, Barreneche C and Petrichenko K 2015 Heating and cooling energy trends and drivers in buildings *Renewable and Sustainable Energy Reviews* **41**

Waite M, Cohen E, Torbey H, Piccirilli M, Tian Y and Modi V 2017 Global trends in urban electricity demands for cooling and heating *Energy* **127**

Ward K, Lauf S, Kleinschmit B and Endlicher W 2016 Heat waves and urban heat islands in Europe: A review of relevant drivers *Science of the Total Environment*

Yang Q, Huang X, Tong X, Xiao C, Yang J, Liu Y and Cao Y 2022 Global assessment of urban trees' cooling efficiency based on satellite observations *Environmental Research Letters* **17**

Zaitchik B F and Tuholske C 2021 Earth observations of extreme heat events: Leveraging current capabilities to enhance heat research and action *Environmental Research Letters* **16**

Zeng Z, Zhang W, Sun K, Wei M and Hong T 2022 Investigation of pre-cooling as a recommended measure to improve residential buildings' thermal resilience during heat waves *Build Environ* **210**

Zhang K, Cao C, Chu H, Zhao L, Zhao J and Lee X 2023 Increased heat risk in wet climate induced by urban humid heat *Nature* **617** 738–42 Online: https://doi.org/10.1038/s41586-023-05911-1

Zhang S and Lin Z 2020 Standard effective temperature based adaptive-rational thermal comfort model *Appl Energy* **264**

Zhao J, Meili N, Zhao X and Fatichi S 2023 Urban vegetation cooling potential during heatwaves depends on background climate *Environmental Research Letters* **18**

Zhao L, Lee X, Smith R B and Oleson K 2014 Strong contributions of local background climate to urban heat islands *Nature*

Zhao L, Oleson K, Bou-Zeid E, Krayenhoff E S, Bray A, Zhu Q, Zheng Z, Chen C and Oppenheimer M 2021 Global multi-model projections of local urban climates *Nat Clim Chang* **11**

Zinzi M, Agnoli S, Burattini C and Mattoni B 2020 On the thermal response of buildings under the synergic effect of heat waves and urban heat island *Solar Energy* **211**

Appendix A. Thermal comfort analysis according to indoor air conditions

An understanding of the adaptive thermal comfort in the local context is required to make decisions on setpoint parameters for cooling, which determines the building system's cooling efficiency and cooling load. In addition to the setpoint air temperature, setpoint relative humidity also affects the thermal comfort of the indoor environment. To quantify thermal comfort in an indoor setting, we utilize Standard Effective Temperature (SET) with several basic assumptions, including the assumption that the mean radiant temperature is equal to the air temperature, an air speed of 0.1 m/s, a metabolic rate of 1 met, and a clothing level of 0.6 clo, representing summer clothing conditions (Ji *et al* 2022). Table A shows the SET values of an indoor setting with air temperature in the range of 22-27 °C and relative humidity in the range of 30% to 70%.

Table A. Standard Effective Temperature (SET, °C) calculation metrics based on a range of indoor air temperatures and relative humidity levels. The color represents the human sensation and physiology of SET values.

SET (°C)		**Indoor Air Temperature (°C)**					
		22	**23**	**24**	**25**	**26**	**27**
Indoor Relative Humidity	**30%**	21.4	22.4	23.4	24.3	25.2	26.1
	40%	21.5	22.5	23.5	24.5	25.5	26.4
	50%	21.6	22.6	23.7	24.7	25.7	26.8
	60%	21.7	22.8	23.8	25.0	26.1	27.2
	70%	21.8	22.9	24.0	25.3	26.5	27.8

SET (°C)	**Sensation**	**Physiology**
25.6-30	Slightly warm, slightly unacceptable	Slight sweat, vasodilation
22.2-25.6	Comfortable, acceptable	Physiological thermal neutrality
17.5-22.2	Slightly cool, slightly unacceptable	Initial vasoconstriction